Summary of Stress Analysis Results for the US-APWR Steam Generator

Non-Proprietary Version

March 2011

Revision History

Revision	Page	Description
0	All	Original Issue
1	Abstract	Revised sentences.
	Table of Contents	Revised table of contents and page numbers.
	List of Tables	Revised list of tables and page numbers.
	List of Figures	Revised list of figures and page numbers.
	1.0 Introduction	Revised sentences.
	2.0 Summary of results	Deleted analysis results of Feedwater Nozzle and Upper Head, and revised analysis results.
	7.2 Materials	Revised materials and material properties.
	7.3 Loads, Load Combinations, and Transients	Revised loads for Inlet/Outlet Nozzle and Channel Head Support, and deleted loads for Lateral Supports, Feedwater Nozzle and Steam Nozzle. Revised table numbers.
	8.2 Stress Analysis	Added programs.
	8.3 Fatigue Analysis Model and Method	Revised table number.
	9.0 Computer Programs Used	Revised programs version No., and added a program.
	10.0 Structural Analysis Results	Deleted analysis results of Feedwater Nozzle and Upper Head, and revised analysis results.
	12.0 References	Revised references.

MITSUBISHI HEAVY INDUSTRIES, LTD.
16-5, Konan 2-chome, Minato-ku
Tokyo 108-8215 Japan

Abstract

This report contains a summary of the structural evaluation of the six Steam Generator (SG) parts.

The evaluations performed were based on the loading conditions defined in the US-APWR SG Design Specification (Reference 4) and on the design procedures per the 2001 Edition of Section III of the ASME Boiler & Pressure Vessel Code up to and including the 2003 addenda, referred to as the ASME Code of Reference, Section III (Reference 1).

The analyses and results presented demonstrate that the six parts of the SG that were evaluated satisfy all of the applicable structural limits of the ASME Code of Reference.

Table of Contents

List of Tables

List of Figures

List of Acronyms

The following list defines the acronyms used in this document.

AVB	Anti Vibration Bar
DCD	Design Control Document
FEA	Finite Element Analysis
FSRF	Fatigue Strength Reduction Factor
LOCA	Loss-of-Coolant Accident
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RT	Radiographic Examination
SG	Steam Generator
SLB	Steam Line Break
SRSS	Square-Root-Of-The-Sum-Of-The-Squares
SSE	Safe Shutdown Earthquake
TSP	Tube Support Plate

1.0 INTRODUCTION

This Technical Report contains a summary of the stress analysis results for the US-APWR Steam Generator (SG). The content of this report follows the ASME guidelines for Design Reports (Section III Division 1 Appendix C).

Figure 1-1 shows the general configuration of the US-APWR SG.

This report provides structural evaluations for six SG parts. The six evaluated SG parts are listed in Table 2-1. This Technical Report summarizes the stress results based upon detailed analyses that demonstrate the validity of the SG component to meet the requirements of the Design Specification (Reference 4).

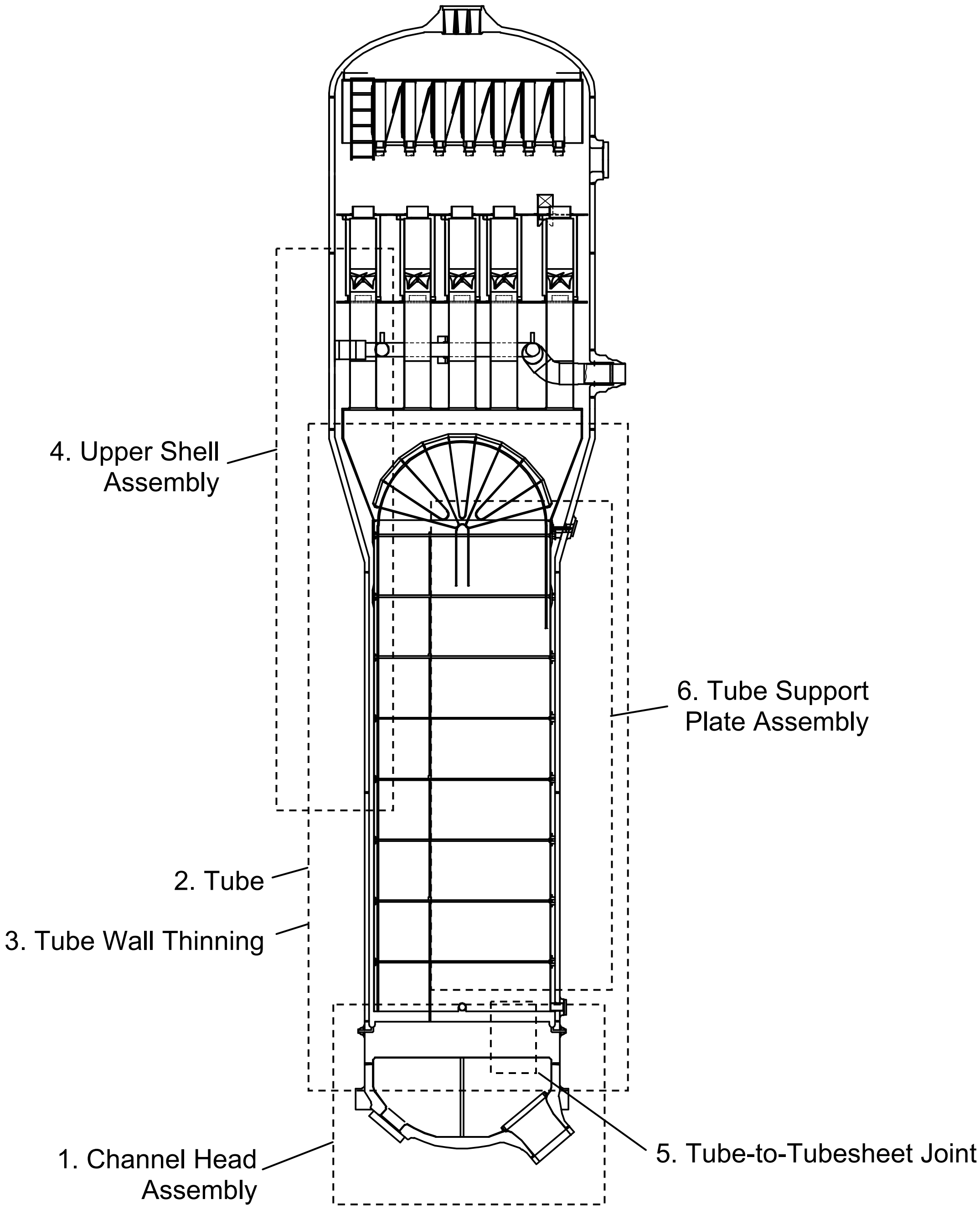


Figure 1-1 SG Evaluated Parts

2.0 SUMMARY OF RESULTS

The six evaluated parts of the SG, along with the most limiting stress results in each, are listed in Table 2-1 below. The structural analysis results for each of these parts are provided in Section 10.

Table 2-1 Summary of Most Limiting Stress Results

Section	Evaluated Part	Max Stress / Allowable Ratio [1]	Highest Fatigue [2] Usage Factor
10.1	Channel Head Assembly		
10.2	Tubes		
10.3	Tube Wall Thinning		
10.4	Upper Shell Assembly		
10.5	Tube-to-Tubesheet Joint		
10.6	Tube Support Plate Assembly		

Note-1: The allowable ratio is the "ratio" of the calculated stress intensity to the allowable stress intensity. Therefore, any ratio less than or equal to 1.0 is acceptable.

$$\text{Ratio} = \frac{\text{Calculated} \cdot \text{Stress} \cdot \text{Intensity}}{\text{Allowable} \cdot \text{Stress} \cdot \text{Intensity}}$$

Note-2: The fatigue calculations performed in this report meet the requirements of the ASME Code of Reference. Environmental fatigue per RG 1.207 will be evaluated separately.

Note-3: Based on primary plus secondary stress limit, excluding thermal bending.

Note-4: Degraded Tube Analysis Results for Tube which has the thickness with 40% defect.

3.0 CONCLUSIONS

The US-APWR SG is designed to the requirements of the ASME Boiler and Pressure Vessel Code, 2001 Edition up to and including the 2003 Addenda for the Design, Service Loadings, Operating Conditions, and Test Conditions as specified in the Design Specification (Reference 4).

From the results summarized in this report and a review of the component design drawings, it is concluded that the US-APWR SG satisfies all of the requirements of the Design Specification.

4.0 NOMENCLATURE

Symbol	Unit	Definition
P_m	ksi	General Primary Membrane Stress
P_L	ksi	Local Primary Membrane Stress
P_b	ksi	Primary Bending Stress
Q	ksi	Secondary Stress
S_m	ksi	Design Stress Intensity
S_y	ksi	Yield Stress
S_u	ksi	Tensile Strength
A_b	in^2	Actual Total Cross-Sectional Area of Bolts at Root of Thread or Section of Least Diameter Under Stress
A_m	in^2	Required Total Design Cross-Sectional Area of Bolts, taken as the greater of A_{m1} and A_{m2}
A_{m1}	in^2	Total cross-sectional area of bolts at root of thread or section of least diameter under stress, required for Design Condition $=W_{m1}/S_b$
A_{m2}	in^2	Total cross-sectional area of bolts at root of thread or section of least diameter under stress, required for gasket seating $=W_{m2}/S_a$
S_t	ksi	Averaged Stress for Bolt (neglecting stress concentration)
$S_t + S_b$	ksi	Tension plus Bending Stress for Bolt (neglecting stress concentration)
W_{m1}	lb	Minimum required bolt load for Design Pressure
W_{m2}	lb	Minimum required bolt load for gasket seating
y_A	-	Thermal Ratcheting Factor
SS	ksi	Thermal Stress Range
α	-	Shape Factor
P	-	Design Pressure
1/3 SSE	-	Level B Service Loading Earthquake
SSE	-	Safe Shutdown Earthquake

5.0 ASSUMPTIONS AND OPEN ITEMS

5.1 Assumptions

The basic modeling assumptions from the detailed analyses are as follows:

1. The inside diameter is taken as the drawing nominal value.
2. The wall thickness is the drawing nominal value.
3. For the particular cases of the primary side parts, cladding less than 10% of the total thickness is not considered in the stress analysis.
4. For the primary side parts, the corrosion allowance is zero.
5. For the secondary side carbon and low alloy steel parts, the corrosion allowance of 0.06 inches is considered.

5.2 Open Items

There are no open items in this Technical Report.

6.0 ACCEPTANCE CRITERIA

The stress intensity acceptance criteria for Class 1 components are specified in NB-3220, NB-3230, and Appendix F of Section III. Table 6-1 lists the stress limits for parts other than bolts and Table 6-2 lists the stress limits for bolts.

Table 6-1 Class 1 Component Stress Limits (other than Bolts)

Condition	Stress Category	Stress Limits	Remarks
Design	P_m	S_m	NB-3221.1
	P_L	1.5 S_m	NB-3221.2
	$P_L + P_b$	αS_m [1) 2)] or 1.5 S_m	NB-3221.3
	Bearing Stress	S_y [6)] or 1.5 S_y [6)]	NB-3227.1(a)
	Shear Stress	0.6 S_m	NB-3227.1(b)
	Pure Shear Stress	0.6 S_m	NB-3227.2(a)
	Triaxial Sress[4)]	4 S_m	NB-3227.4
Level A & B	$P_L + P_b + Q$	3 S_m	NB-3222.2
	Thermal Ratchet, SS	[5)] $S_y \times y_A$	NB-3222.5
	Usage Factor	1.0	NB-3222.4
	Bearing Stress	S_y [6)] or 1.5 S_y [6)]	NB-3227.1(a)
	Shear Stress	0.6 S_m	NB-3227.1(b)
	Pure Shear Stress	0.6 S_m	NB-3227.2(a)
	Triaxial Sress[4)]	4 S_m	NB-3224.3
Level B	P_m	1.1 S_m	NB-3223
	P_L	1.5 (1.1 S_m)	NB-3223
	$P_L + P_b$	α (1.1S_m)[1) 2)] or 1.5 (1.1 S_m)	NB-3223
Level C	P_m	Max (1.2 S_m, S_y) Max (1.1 S_m, 0.9 S_y)[3)]	NB-3224.1
	P_L	Max (1.8 S_m, 1.5 S_y)	NB-3224.1
	$P_L + P_b$	Max (α (1.2 S_m), α S_y) [1) 2)] or Max (1.8 S_m, 1.5 S_y)	NB-3224.1
	Bearing Stress	S_y [6)] or 1.5 S_y [6)]	NB-3227.1(a)
	Shear Stress	0.6 S_m	NB-3227.1(b)
	Pure Shear Stress	0.6 S_m	NB-3227.2(a)
	Triaxial Sress[4)]	4.8 S_m	NB-3224.3
Level D	P_m	For ferritic materials, 0.7 S_u For austenitic and high alloy steels, Min (2.4 S_m, 0.7 S_u)	NB-3225 (Appendix F-1331.1)
	P_L	For ferritic materials, 1.5 (0.7 S_u) For austenitic and high alloy steels, 1.5 Min (2.4 S_m, 0.7 S_u)	
	$P_L + P_b$	For ferritic materials, 1.5 (0.7 S_u) For austenitic and high alloy steels, 1.5 Min (2.4 S_m, 0.7 S_u)	
	Pure Shear	0.42 S_u	
Test	P_m	0.9 S_y	NB-3226

	$P_m + P_b$	(1.35 S_y) - for $P_m \leq 0.67\ S_y$ (or 0.9 α S_y for non-rectangular sections) (2.15 S_y -1.2 P_m) - for 0.67 $S_y < P_m \leq 0.9\ S_y$	
	Bearing Stress	S_y 6) or 1.5 S_y 6)	NB-3227.1(a)
	Shear Stress	0.6 S_m	NB-3227.1(b)
	Pure Shear Stress	0.6 S_m	NB-3227.2(a)
	Triaxial Sress 4)	4 S_m	NB-3227.4

Note-1 The shape factor of α for solid rectangular sections is 1.5, α shall not exceed 1.5.

Note-2 "α" is considered where stresses are classified as primary bending.

Note-3 The stress limits for pressure loading alone for ferritic material.

Note-4 NB-3227.4 states that the Triaxial Stress limit is 4 S_m and does not apply to Level D. NB-3224.3 states the Level C limit is 4.8 S_m.

Note-5 NB-3222.5 requires evaluation of Thermal Stress Ratcheting for Level A Service Loads. In all cases where elastic analysis indicates that the primary membrane stress is less than S_m and the primary plus secondary stress is less than 3 S_m, then thermal stress ratcheting will not occur.

Note-6 S_y when the distance to a free edge is less than the distance over which the bearing load is applied; 1.5 S_y when the distance to a free edge is larger.

Table 6-2 Class 1 Bolt Stress Limits

Condition	Stress Category	Stress Limits	Remarks
Design	A_b	A_m	NB-3231, E-1000
Level A & B	Average Service Stress 1), S_t	2 S_m	NB-3232.1
	Max Service Stress 1), $S_t + S_b$	3 S_m	NB-3232.2
	Fatigue Usage Factor 2)	1.0	NB-3232.3
Level C	Average Service Stress 1), S_t	2 S_m	NB-3234
	Max Service Stress 1), $S_t + S_b$	3 S_m	NB-3234
Level D	Average Tensile Stress 3), S_t	Min (S_y, 0.7 S_u)	NB-3235 & F-1335.1
	Max Tensile Stress 3), $S_t + S_b$	S_u	NB-3235 & F-1335.1
	Average bolt shear	Min (0.6 S_y, 0.42 S_u)	F-1335.2
	Combined tensile and shear	$f_t^2/F_{tb}^2 + f_v^2/F_{vb}^2 \leq 1$ 4)	F-1335.3
	Distance from bolt center to edge	d [0.5 + 1.2 (fp / S_u)] 5)	F-1335.4(a)
	Nominal bearing stress	2.1 S_u	F-1335.4(b)

Note-1 Includes preload, pressure, and differential thermal expansion, excludes stress concentrations.

Note-2 Includes a fatigue strength reduction factor of 4 for the threads.

Note-3 Includes preload, pressure, differential thermal expansion, and prying action produced by deformation of the connected parts, excludes stress concentrations.

Note-4 f_t=computed tensile stress, f_v=computed shear stress, F_{tb}=allowable tensile stress at operating temperature, F_{vb}=allowable shear stress at operating temperature.

Note-5 d= nominal bolt diameter; fp = nominal bearing stress.

7.0 DESIGN INPUT

7.1 Geometry

The US-APWR SG basic design drawings used to supply dimensions for the stress analyses are taken from Reference 5. Figures describing the detailed geometry and dimensions of the parts evaluated are provided in Section 10.

7.2 Material

The materials of construction for the SG pressure boundary and internals are listed in Table 7-1

Table 7-1 Materials of Construction

Part or Assembly	Material
Channel Head, Primary Nozzles & Manways	SA-508 Grade 3 Class 2
Tubesheet	SA-508 Grade 3 Class 2
Upper Head, Nozzles & Manways	SA-508 Grade 3 Class 2
Transition Cone	SA-508 Grade 3 Class 2
Secondary Shell Barrels	SA-508 Grade 3 Class 2
Manway Covers	SA-533 Type B Class 2
Manway and Hand Hole Studs	SA-193 Grade B7
Primary Nozzle Safe Ends	SA-182 Grade F316
Tubes	Alloy 690TT SB-163 UNS N06690
Divider Plate	Alloy 690TT SB-168 UNS N06690
Feedwater Nozzle Thermal Sleeve	Alloy 690TT SB-167 UNS N06690
Tube Supports	SA-240 Type 405
Stay Rods	SA-193 Grade B7
Feedwater Distribution Ring	SA-335 Grade P22
Wrapper and Supports	SA-516 Grade 70

The material strength properties used in the stress analyses are provided in Tables 7-2 through 7-7, below. The strength properties were obtained from ASME Section II (Ref 2).

Table 7-2 Material Properties for SA-508 Grade 3, Class 2
(Channel head, tubesheet, cone, head, barrels, etc.)

Temperature, °F	S_m (ksi)	S_y (ksi)	S_u (ksi)
70	30.0	65.0	90.0
100	30.0	65.0	90.0
200	30.0	61.2	90.0
300	30.0	59.1	90.0
400	30.0	57.5	90.0
500	30.0	56.1	90.0
600	30.0	54.7	90.0
650	30.0	53.9	90.0

Table 7-3 Material Properties for SA-533 Type B, Class 2
(Manway Covers)

Temperature, °F	S_m (ksi)	S_y (ksi)	S_u (ksi)
70	30.0	70.0	90.0
100	30.0	70.0	90.0
200	30.0	65.9	90.0
300	30.0	63.7	90.0
400	30.0	61.9	90.0
500	30.0	60.4	90.0
600	30.0	58.9	90.0
650	30.0	58.0	90.0

Table 7-4 Material Properties for Alloy 690TT SB-163
UNS N06690 (Tubes)

Temperature, °F	S_m (ksi)	S_y (ksi)	S_u (ksi)
70	26.7	40.0	85.0
100	26.7	40.0	85.0
200	26.7	36.2	85.0
300	26.7	34.1	84.0

Table 7-4 Material Properties for Alloy 690TT SB-163 UNS N06690 (Tubes)

Temperature, °F	S_m (ksi)	S_y (ksi)	S_u (ksi)
400	26.7	32.7	82.0
500	26.7	31.9	80.8
600	26.7	31.5	80.2
650	26.7	31.5	80.0

Table 7-5 Material Properties for Alloy 690TT SB-167, 168 UNS N06690 (not tubes)

Temperature, °F	S_m (ksi)	S_y (ksi)	S_u (ksi)
70	23.3	35.0	85.0
100	23.3	35.0	85.0
200	23.3	31.7	85.0
300	23.3	29.8	84.0
400	23.3	28.6	82.0
500	23.3	27.9	80.8
600	23.3	27.6	80.2
650	23.3	27.5	80.0

Table 7-6 Material Properties for SA-182 Grade F316 (Primary Nozzle safe ends)

Temperature, °F	S_m (ksi)	S_y (ksi)	S_u (ksi)
70	20.0	30.0	75.0
100	20.0	30.0	75.0
200	20.0	25.9	75.0
300	20.0	23.4	72.9
400	19.3	21.4	71.9
500	18.0	20.0	71.8
600	17.0	18.9	71.8
650	16.6	18.5	71.8

Table 7-7 Material Properties for SA-240 Type 405 (Tube Supports)

Temperature, °F	S_m (ksi)	S_y (ksi)	S_u (ksi)
70	16.7	25.0	60.0
100	16.7	25.0	60.0
200	15.3	23.0	60.0
300	14.8	22.2	58.8
400	14.5	21.8	57.8
500	14.3	21.5	56.9
600	14.0	21.0	55.5
650	13.8	20.7	54.4

7.3 Loads, Load Combinations, and Transients

The loads, load combinations and transients are defined in the Design Specification. Following is a summary of those used for the SG structural evaluations.

7.3.1 Pressure Loads and Temperature

Table 7-8 Pressures and Temperatures

Parameter	Value
Primary side design pressure	2500 psia (2485 psig)
Primary side design temperature	650°F
Secondary side design pressure	1200 psia (1185 psig)
Secondary side design temperature	568°F
Maximum primary-to-secondary differential pressure	1600 psi
Maximum secondary-to-primary differential pressure	670 psi
Maximum primary-to-secondary temperature	650°F
Primary side hydrostatic test pressure	3122 psia (3107 psig)
Secondary side hydrostatic test pressure	1497 psia (1482 psig)
Minimum hydrostatic test temperature	70°F

Note: hydrotest to be conducted with opposite side at atmospheric pressure

7.3.2 External Mechanical Loads

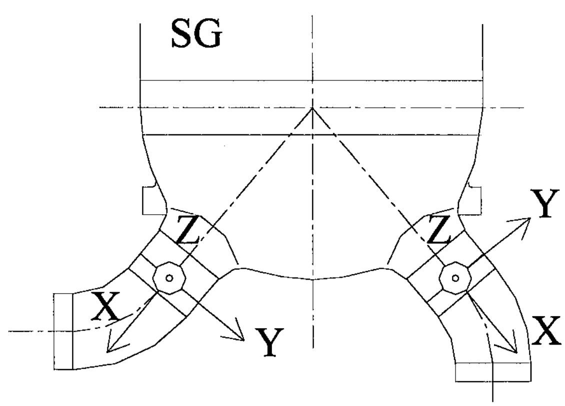
The external loads are dead weight, thermal expansion loads, seismic loads and accident loads. The external loads used in this report come from the Design Specification.

Table 7-9 through 7-11 provide the external loads on the SG.

The bolt preload values for the manway studs is the minimum required bolt load for the design pressure calculated in accordance with Article E-1000 of the ASME code.

Table 7-9 Loads Applied to the Primary Inlet Nozzle

Loading			Fx (kips)	Fy (kips)	Fz (kips)	Mx (kips・in)	My (kips・in)	Mz (kips・in)
Dead Weight	Loop-A,D							
	Loop-B,C							
Thermal	Loop -A,D	Gr.1						
		Gr.2						
		Gr.3						
		Gr.4						
		Gr.5						
		Gr.6						
		Gr.7						
		Gr.8						
		Gr.9-1						
		Gr.9-2						
	Loop -B,C	Gr.1						
		Gr.2						
		Gr.3						
		Gr.4						
		Gr.5						
		Gr.6						
		Gr.7						
		Gr.8						
		Gr.9-1						
		Gr.9-2						
Seismic (1/3 SSE)								
Seismic (SSE)								
Accident								



SG Inlet Nozzle SG Outlet Nozzle

Table 7-10 Loads Applied to the Primary Outlet Nozzle

Loading			Fx (kips)	Fy (kips)	Fz (kips)	Mx (kips・in)	My (kips・in)	Mz (kips・in)
Dead Weight	Loop-A,D							
	Loop-B,C							
Thermal	Loop -A,D	Gr.1						
		Gr.2						
		Gr.3						
		Gr.4						
		Gr.5						
		Gr.6						
		Gr.7						
		Gr.8						
		Gr.9-1						
		Gr.9-2						
	Loop -B,C	Gr.1						
		Gr.2						
		Gr.3						
		Gr.4						
		Gr.5						
		Gr.6						
		Gr.7						
		Gr.8						
		Gr.9-1						
		Gr.9-2						
Seismic (1/3 SSE)								
Seismic (SSE)								
Accident								

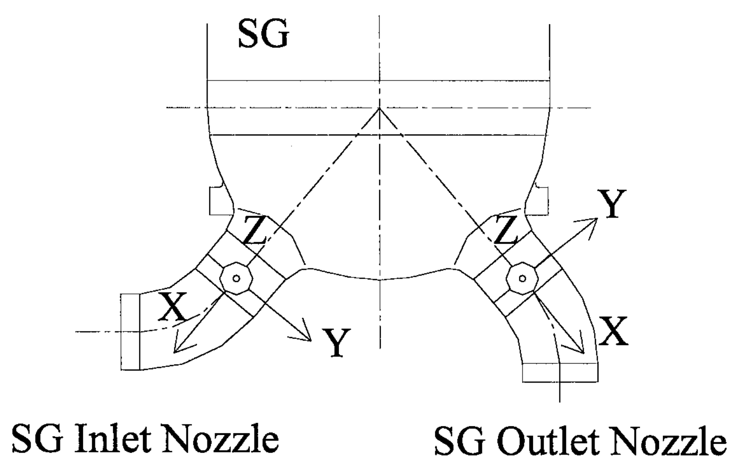


Table 7-11 Loads Applied to the Channel Head Support Pad-1

Loading			Fx (kips)	Fy (kips)	Fz (kips)	Mx (kips・in)	My (kips・in)	Mz (kips・in)
Dead Weight	Loop-A,D							
	Loop-B,C							
Thermal	Loop-A,D	Gr.1						
		Gr.2						
		Gr.3						
		Gr.4						
		Gr.5						
		Gr.6						
		Gr.7						
		Gr.8						
		Gr.9-1						
		Gr.9-2						
	Loop-B,C	Gr.1						
		Gr.2						
		Gr.3						
		Gr.4						
		Gr.5						
		Gr.6						
		Gr.7						
		Gr.8						
		Gr.9-1						
		Gr.9-2						
Seismic (1/3 SSE)								
Seismic (SSE)								
Accident								

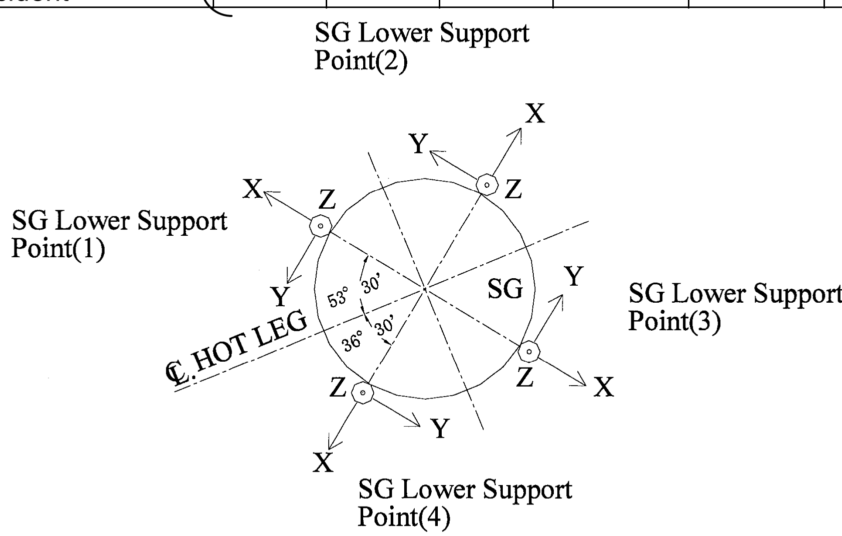


Table 7-11 Loads Applied to the Channel Head Support Pad-2

Loading			Fx (kips)	Fy (kips)	Fz (kips)	Mx (kips・in)	My (kips・in)	Mz (kips・in)
Dead Weight	Loop-A,D							
	Loop-B,C							
Thermal	Loop-A,D	Gr.1						
		Gr.2						
		Gr.3						
		Gr.4						
		Gr.5						
		Gr.6						
		Gr.7						
		Gr.8						
		Gr.9-1						
		Gr.9-2						
	Loop-B,C	Gr.1						
		Gr.2						
		Gr.3						
		Gr.4						
		Gr.5						
		Gr.6						
		Gr.7						
		Gr.8						
		Gr.9-1						
		Gr.9-2						
Seismic (1/3 SSE)								
Seismic (SSE)								
Accident								

Table 7-11 Loads Applied to the Channel Head Support Pad-3

Loading			Fx (kips)	Fy (kips)	Fz (kips)	Mx (kips・in)	My (kips・in)	Mz (kips・in)
Dead Weight	Loop-A,D							
	Loop-B,C							
Thermal	Loop-A,D	Gr.1						
		Gr.2						
		Gr.3						
		Gr.4						
		Gr.5						
		Gr.6						
		Gr.7						
		Gr.8						
		Gr.9-1						
		Gr.9-2						
	Loop-B,C	Gr.1						
		Gr.2						
		Gr.3						
		Gr.4						
		Gr.5						
		Gr.6						
		Gr.7						
		Gr.8						
		Gr.9-1						
		Gr.9-2						
Seismic (1/3 SSE)								
Seismic (SSE)								
Accident								

Table 7-11 Loads Applied to the Channel Head Support Pad-4

Loading			Fx (kips)	Fy (kips)	Fz (kips)	Mx (kips・in)	My (kips・in)	Mz (kips・in)
Dead Weight	Loop-A,D							
	Loop-B,C							
Thermal	Loop-A,D	Gr.1						
		Gr.2						
		Gr.3						
		Gr.4						
		Gr.5						
		Gr.6						
		Gr.7						
		Gr.8						
		Gr.9-1						
		Gr.9-2						
	Loop-B,C	Gr.1						
		Gr.2						
		Gr.3						
		Gr.4						
		Gr.5						
		Gr.6						
		Gr.7						
		Gr.8						
		Gr.9-1						
		Gr.9-2						
Seismic (1/3 SSE)								
Seismic (SSE)								
Accident								

7.3.3 Thermal and Pressure Transient Loads

The design transients used in the structural evaluations are listed in Table 7-12. These transients were determined based on a 60-year plant operating period and are classified as ASME Level A, Level B, Level C, Level D service conditions, or Test conditions, depending on the expected frequency of occurrence and severity of the event.

Table 7-12 Design Transients

Mark	Transient	Occurrence	Remark
Level A Service Conditions			
I-a	Plant heat-up (50F/h)	120	
I-b	Plant cooldown (100F/h)	120	Includes Transient for Loss of offsite power with natural circulation cooldown (10 times) and Safe shutdown (1 time)
I-c-1	Ramp load increase between 15% and 100% of full power (5% or full power per minute)	600	
I-c-2	Ramp load increase between 50% and 100% of full power (5% or full power per minute)	19,200	
I-d-1	Ramp load decrease between 15% and 100% of full power (5% or full power per minute)	600	
I-d-2	Ramp load decrease between 50% and 100% of full power (5% or full power per minute)	19,200	
I-e	Step load increase of 10% of full power	600	
I-f	Step load decrease of 10% of full power	600	
I-g	Large step load decrease with turbine bypass	60	
I-h i)	Steady-state fluctuations and load regulation (Steady state fluctuations)	1×10^6	$P_P \pm 50$psi, T_{hot},T_{cold}, $T_{ave} \pm 3.1$F
I-h ii)	Steady-state fluctuations and load regulation (Load regulation)	8×10^5	
I-i	Main feedwater cycling	2,100	
I-j	Refueling	60	Water is replaced in 10minutes
I-k	Ramp load increase between 0% and 15% of full power	600	
I-l	Ramp load decrease between 0% and 15% of full power	600	
I-m	RCP startup	3,000	
I-n	RCP shutdown	3,000	
I-o	Core lifetime extension	60	
I-p	Primary leakage test	120	
I-q	Turbine roll test	10	
I-s	Secondary leakage test	120	
Level B Service Conditions			
II-a	Loss of load	60	
II-b	Loss of offsite power	60	
II-c	Partial loss of reactor coolant flow	30	
II-d i)	Reactor trip from full power With no inadvertent cooldown	60	

Table 7-12 Design Transients

II-d ii)	Reactor trip from full power With cooldown and no safety injection	30	Includes Transient for excessive feedwater flow
II-d iii)	Reactor trip from full power With cooldown and safety injection	10	
II-e	Inadvertent RCS depressurization	30	
II-f	Control rod drop	30	
II-g	Inadvertent safeguards actuation	30	
II-h	Emergency feedwater cycling	700	
II-i	Cold over-pressure	30	
II-j	Excessive feedwater flow	—	Covered by Transient for reactor trip from full power ii)
II-k	Loss of offsite power with natural circulation cooldown	—	Covered by Transient for plant cooldown
II-l	Partial loss of emergency feedwater	30	Use Figure for Transient of loss of offsite power
II-m	Safe Shutdown	—	Covered by Transient for plant cooldown
Level C Service Condition			
III-a	Small loss of coolant accident	5	
III-b	Small steam line break	5	
III-c	Complete loss of flow	5	
III-d	Small feedwater line break	5	
III-e	SG tube rupture	5	
Level D Service Condition			
IV-a	Large loss of coolant accident	1	
IV-b	Large steam line break	1	
IV-c	RCP locked rotor	1	
IV-d	Control rod ejection	1	
IV-e	Large feedwater line break	1	
Test Condition			
V-a	Primary-side hydrostatic test	10	
V-b	Secondary-side hydrostatic test	10	

7.3.4 Load Combinations

The loading conditions consist of various combinations of pressure, thermal and external loads. The loads combinations considered in the analysis are listed in Table 7-13.

The names used for the external loads refer directly to the names specified in Table 7-9 through 7-11.

Table 7-13 Load Combinations

System Operating Condition	Service Stress Limit	Service Loading Combination
Design	Design	Design Pressure Dead Weight Loads Mechanical Loads Thermal Loads[1)]
Normal	Level A	Level A Thermal & Pressure Transients Dead Weight Loads Mechanical Loads Thermal Loads[1)]
Upset	Level B	Level B Maximum Pressure[2)] Level B Thermal & Pressure Transients Dead Weight Loads Mechanical Loads Thermal Loads[1)] Seismic(1/3 SSE) Loads
Emergency	Level C	Level C Maximum Pressure Level C Thermal & Pressure Transients[3)] Dead Weight Loads Mechanical Loads Thermal Loads[1)]
Faulted	Level D	Level D Maximum Pressure Dead Weight Loads Mechanical Loads Thermal Loads[1)] ±SRSS(Seismic(SSE) Loads + Accident Loads[4)])
Test	Test	Hydrostatic Test Pressure

Note-1; Applied to the nozzle within the limits of reinforcement for the primary stress evaluation.
Note-2; Applied for the primary stress evaluation.
Note-3; Applied for the bolts instead of Maximum Pressure.
Note-4; If more than one Accident Loads, each are to be analyzed separately.

8.0 METHODOLOGY

The ABAQUS computer program was used to determine loads, temperature distributions, stresses, and deformations. ABAQUS is a general purpose finite element computer program used by MHI in the design and analysis of nuclear components. ABAQUS is available in the public domain and has been used by MHI for U.S. replacement SG and replacement reactor vessel closure head projects.

8.1 Heat Transfer Coefficients and Thermal Analysis

Heat transfer coefficients on the inner and outer surfaces of the component are required to define the temperature distributions during transients. Classical Handbook heat transfer equations (Reference 8) were used to calculate the heat transfer coefficients.

Finite element thermal analyses were performed for all Level A and Level B transients to define the time-dependent temperature distributions in the structure. The primary and secondary fluid temperature versus time curves were applied to all wetted surfaces with appropriate heat transfer coefficients as discussed above. The outside surfaces under the vessel insulation were considered adiabatic.

8.2 Stress Analysis

Finite element stress analyses were performed for given loads and boundary conditions. The thermal loads were input from the thermal solution into each node of the structural model. The calculation of NB-3200 stress intensities, stress classifications, and stress evaluations were performed using a set of in-house proprietary computer programs (CLASS2D, CLASS3D, EDITSTRS, EVALPRI, EVALSEFAV, RATCHET, ASMETEMP and EB3500). These programs are described in Section 9.

Figure 8-1 shows the stress evaluation process.

CLASS2D and CLASS3D classify the stresses resulting from pressure, thermal loads, and externally applied forces and moments. EDITSTRS creates input files for the stress evaluation programs EVALPRI, EVALSEFAV, and RATCHET. EVALPRI and EVALSEFAV quantify the primary stress intensities, quantify the primary plus secondary stress ranges, and perform the fatigue evaluation. The RATCHET program was used for the thermal ratchet evaluation.

Detailed assumptions associated with the finite element model development and mesh refinement are documented in the detailed calculations. Finite element models were verified by hand calculations using handbook equations.

Figure 8-1 Stress Evaluation Process

8.3 Fatigue Analysis Model and Method

The fatigue analysis was based on the rules of NB-3216.2 and NB-3222.4(e) of ASME Section III (Ref 1). These rules require calculation of the total stress, including the peak stress, to determine the allowable number of stress cycles for the specified service loadings at every point in the structure. In some cases, a fatigue strength reduction factor (FSRF) was used where the peak stress could not be accurately calculated. In these cases, the factor was applied to the surface stress produced by a linear stress distribution (through the wall thickness) that produced the identical displacement / rotation of the section (i.e. equivalent structural equilibrium).

The design transients for ASME Level A and B service conditions (Table 7-12) were used in the evaluation of cyclic fatigue. The effect of 300 cycles of a 1/3 SSE seismic event was included in the evaluation of cyclic fatigue, treated as a Level B service condition. The number of cycles assumed for the 1/3 SSE seismic event was based on a fatigue usage factor equivalent to that for a single SSE event of 20 cycles.

9.0 COMPUTER PROGRAMS USED

Refer to Figure 8-1 for a visual description of the Stress Evaluation Process. Table 9-1 provides a brief description of each of the computer programs used.

Table 9-1 Computer Program Description

No.	Program Name	Version	Description
1	ABAQUS	6.7-1	ABAQUS is a general purpose finite element computer code that performs a wide range of linear and nonlinear engineering simulations
2	CLASS2D	4.0	CLASS2D is an MHI Code for classifying the stresses for axisymmetric models
3	CLASS3D	4.0	CLASS3D is an MHI Code for classifying the stresses for 3D solid models
4	EDITSTRS	4.0	EDITSTRS is an MHI Code that creates input files for the stress evaluation programs
5	EVALPRI	7.0	EVALPRI is an MHI Code that performs the primary stress evaluation
6	EVALSEFAV	7.0	EVALSEFAV is an MHI Code that performs the secondary stress and fatigue evaluation
7	RATCHET	8.0	RATCHET is an MHI Code that evaluates thermal stress ratcheting
8	ASMETEMP	1.0	ASMETEMP is an MHI Code that creates temperature files for the stress evaluation program
9	EB3500	3.0	EB3500 is an MHI Code that performs the general primary membrane stress evaluation.

All these computer programs were verified and validated and are maintained in compliance with the MHI quality assurance program. The computer programs were validated using one of the methods described below. Verification tests demonstrate the capability of the computer program to produce valid results for the test problems encompassing the range of permitted usage defined by the program documentation.

- Hand calculations
- Known solution for similar or standard problem
- Acceptable experimental test results
- Published analytical results
- Results from other similar verified programs

10.0 STRUCTURAL ANALYSIS RESULTS

This Section summarizes the results of the analyses for the six parts of the SG. The stress calculations were carried out by a combination of finite element analysis (FEA) and hand calculations. The general element types used for creation of the finite element model were the 20-node quadratic heat transfer brick and the 20-node quadratic brick from the ABAQUS element library, for heat transfer analysis and structural analysis, respectively.

The reported results are generally conservative and larger than the actual values if more detailed calculations were performed; but since they all meet the ASME Code allowable limits, further analysis is not necessary.

10.1 Channel Head Assembly

10.1.1 Modeling & Analysis

Figure 10.1-1 Channel Head Assembly Dimensions

Figure 10.1-2 Channel Head Assembly Dimensions

Figure 10.1-3 Channel Head Assembly Dimensions

Figure 10.1-4 Channel Head Finite Element Model

Figure 10.1-5 Channel Head Finite Element Model

10.1.2 Stress Results

The stress-to-allowable ratios (calculated stress divided by allowable value), the fatigue cumulative usage factors, and the thermal stress ratchet results for the most limiting locations in the SG channel head are summarized in Table 10-1.

Table 10-1 Channel Head Assembly Result Summary

Condition	Part	Stress-to-Allowable Ratio				Fatigue	Thermal Ratchet
		Primary Stress			Primary + Secondary Stress		
		P_m	P_L or P_L+P_b	Triaxial Stress	P_L+P_b+Q	Usage Factor	
Design							
Level A / B							
Level C							

Table 10-1 Channel Head Assembly Result Summary

Condition	Part	Stress-to-Allowable Ratio				Fatigue	Thermal Ratchet
		Primary Stress			Primary + Secondary Stress		
		P_m	P_L or P_L+P_b	Triaxial Stress	P_L+P_b+Q	Usage Factor	
Level D							
Test							

10.2 Tubes

10.2.1 Modeling and Analysis

Figure 10.2-1 Tube Model Dimensions

Figure 10.2-2 Tube Finite Element Model

Figure 10.2-3 Tube Model Evaluation Cross Sections

10.2.2 Stress Results

The stress-to-allowable ratios (calculated stress divided by allowable value), the fatigue cumulative usage factors, and the thermal stress ratchet results for the most limiting SG tube locations are summarized in Table 10-2.

Table 10-2 Tube Result Summary

Condition	Part	Stress-to-Allowable Ratio				Fatigue	Thermal Ratchet
		Primary Stress			Primary plus Secondary Stress		
		P_m	P_L or P_L+P_b	Triaxial Stress	P_L+P_b+Q	Usage Factor	
Design							
Level A / Level B							
Level C							
Level D							
Test							

10.3 Tube Wall Thinning (RG 1.121 Analysis)

10.3.1 Tube Evaluation Methodology

10.3.2 Stress Results

10.4 Upper Shell Assembly (Shell / Cone / Shell)

10.4.1 Modeling and Analysis

Figure 10.4-1 Upper Shell Assembly Dimensions

Figure 10.4-2 Upper Shell Assembly Finite Element Model

10.4.2 Stress Results

The stress-to-allowable ratios (calculated stress divided by allowable value), the fatigue cumulative usage factors, and the thermal stress ratchet results for the most limiting locations in the SG upper shell assembly are summarized in Table 10-4.

Table 10-4 Upper Shell Assembly Result Summary

Condition	Part	Stress-to-Allowable Ratio				Fatigue	Thermal Ratchet
		Primary Stress			Primary + Secondary Stress		
		P_m	P_L or P_L+P_b	Triaxial Stress	P_L+P_b+Q	Usage Factor	
Design							
Level A / B							
Level C							
Level D							

Table 10-4 Upper Shell Assembly Result Summary

Condition	Part	Stress-to-Allowable Ratio				Fatigue	Thermal Ratchet
		Primary Stress			Primary + Secondary Stress		
		P_m	P_L or P_L+P_b	Triaxial Stress	P_L+P_b+Q	Usage Factor	
Test							

10.5 Tube-to-Tubesheet Joint

10.5.1 Modeling and Analysis

Figure 10.5-1 Tube-to-Tubesheet Joint Dimensions

Figure 10.5-2 Tube-to-Tubesheet Joint Finite Element Model

10.5.2 Stress Results

The stress-to-allowable ratios (calculated stress divided by allowable value), and the fatigue cumulative usage factor for the most limiting locations in the tube-to-tubesheet joint are summarized in Table 10-5.

Table 10-5 Tube-to-Tubesheet Joint Result Summary

Condition	Stress-to-Allowable Ratio				Fatigue
	Primary Stress			Primary plus Secondary Stress	
	P_m	P_L or P_L+P_b	Triaxial Stress	P_L+P_b+Q	Usage Factor
Design					
Level A / Level B					
Level C					
Level D					
Test					

10.6 Tube Support Plate Assembly

10.6.1 Modeling and Analysis

Figure 10.6-1 Tube Support Plate Assembly Dimensions

Figure 10.6-2 TSP Assembly Finite Element Model

10.6.2 Stress Results

The tube support plate and stay rod stress-to-allowable ratios (calculated stress divided by allowable value) are summarized in Table 10-6. The in-plane structural limits for the tube support plate are based on empirical data (for Level B no yielding is permitted; for Level D deformation is permitted but no tube contact).

Table 10-6 Tube Support Plate Assembly Result Summary

Evaluated direction	Condition	Part	Evaluation	Ratio (Result / Limit)

11.0 FRACTURE MECHANICS ASSESSMENT

When the bulk fluid temperature drops to a low level, brittle failure becomes a concern. Events that are analyzed for brittle fracture include heatup / cooldown and the primary & secondary leak tests. For such cases, non-ductile failure evaluations are carried out for postulated flaws of several sizes. The analysis is normally based on a flaw size equal to 1/4 the thickness of the component. In the portions where this flaw size is overly conservative, a smaller flaw size is evaluated. These smaller flaws are selected with consideration of the current inspection techniques. This approach is in accordance with the rules of ASME Section III Appendix-G.

12.0 REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components, 2001 Edition through 2003 Addenda
2. ASME Boiler and Pressure Vessel Code, Section II Material Specification, 2001 Edition through 2003 Addenda
3. N0-FB10L01 Rev.3, "US-APWR General ASME Design Specification for Class 1 and CS Components", February 2011
4. N0-F400L01, Rev.5, "US-APWR Steam Generator ASME Design Specification", February 2011
5. N0-F400L03 Rev.4, "Steam Generator Equipment Specification", October 2010
6. SIMULIA, "ABAQUS Analysis User's manual", Version 6.7, 2007
7. "Manual of Steel Construction", Eighth Edition, American Institute of Steel Construction Inc.
8. Warren M. Rohsenow, James P. Hartnett and Yung I. Cho, "Handbook of Heat Transfer", Third Edition, McGraw Hill, 1998